17th UK Heat Transfer Conference (UKHTC2021)
4-6 April 2022, Manchester, UK

NUMERICAL ANALYSIS OF A FREE FALLING WATER-DROPLET IN DIFFERENT TEMPERATURES

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ABSTRACT

Water droplet is a common phenomenon in engineering. The characteristic of water droplet before impinging on wall is important for impinging behavior and ice formation of water droplet in different temperatures. In this paper, a two phase flow of air and water droplet is modeled, and it is laminar, incompressible, and with gravity. The level-set method is used to describe the interface between air and water droplet. The heat transfer in fluid is also calculated through the multi-physical field based on non-isothermal flow coupling. The temperature of air material model is from 200K to 1600K. For water material, the freezing characteristic parameters are added to the system default value. The deformation grid domain is used to define the deformation of water droplet, and its mesh is based on the principle of fluid dynamics refinement, the boundary layer grids are set at the boundary of water droplet. During analysis, air temperature varies from room temperature to freezing temperature. The air temperature is respectively set at 293.15K, 283.15K, 263.15K, 253.15K and 243.15K. With initial temperature at 283.15K, the falling behavior of water droplet in the different temperature air is analyzed by the two phase flow model. During falling process, the shape, temperature and velocity of water droplet are affected by its around air. The time span is from 0 s to 0.10 s. Initially, the water droplet is round at t=0 s. At the last, it is straw hat shape in room temperature at t=0.10 s, but it is human face shape in freezing temperatures at t=0.10 s. Compared with room temperature, water droplet in freezing temperatures has the higher falling velocity, larger Reynolds number, larger Froude number, larger Weber number and lower Ohnesorge number. There are great differences in the temperature distributions. There are also obvious differences in the field temperature and water droplet inner pressure. The analysis results reveal the changes of shape, falling velocity, internal pressure and flow field temperature of water droplet in the short time span. It is helpful to study the next behavior of water droplet in long time span, different temperatures, and the impinge on different walls.

1. INTRODUCTION

Water droplet is a common liquid form in nature and engineering applications. The dynamic freezing dynamics of water droplet on different temperature surfaces is a scientific problem, which involves various engineering fields such as ship, airplane and other transportation. The freezing of water droplet brings great challenge to scientists, and the study of dynamic freezing can provide scientific basis for deicing and anti icing[1]. The freezing process of water droplet can be divided into two main stages: free falling before impinging on the cold wall, crystallization and freezing process after contact. It is generally believed that the shape of the falling water drops will deform from the beginning of landing, and the deformation order is spherical, ellipsoidal and spherical cap/ellipsoidal cap[2-3]. When it comes into contact with the wall at room temperature, it will occur successively: adhesion, rebound, spreading and splashing[4]. When the wall temperature is lower than freezing point, similar to static freezing, the freezing process of water droplet impacting cold surface is most affected by the wall temperature and ambient temperature. However, only when the wall temperature is further reduced, the effect of impact velocity on freezing will be weakened[5]. Water droplet has different shapes, ice formation, vibration and noise during impact[6].The free falling process of water droplet is an important work to study the impact, spreading and freezing of water droplet.

In this paper, the falling, deformation and temperature change of water droplet in different freezing environment are studied and compared. The two-phase flow method was used to study the

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characteristics of falling water droplets before impact. Meanwhile, considering the heat transfer in the flow field, the hydrodynamics characteristics of the whole droplet are discussed..

2. FORCE ANALYSIS OF FALLING DROPLET

Water droplet in air is affected by gravity F_1, buoyancy F_2 and drag F_3. These forces acting on the droplet can be expressed by the following formulas[7],

$$M_d \frac{du_d}{dt} = F_1 + F_2 + F_3 \tag{1}$$

$$F_1 = \rho_d V_d g \tag{2}$$

$$F_2 = \rho_g V_d g \tag{3}$$

$$F_3 = -\frac{1}{2} C_d A_d \rho_a (u_d - u_a)|u_d - u_a| \tag{4}$$

Here, M_d is water droplet's mass (kg), u_d is water droplet's velocity (m/s), u_a is air flow velocity (m/s), A_d is surface area of water droplet in the direction of motion (m^2), V_d is water droplet's volume (m^3), ρ_a is air density (kg/m^3), g is gravity acceleration, C_d is drag coefficient, and the drag coefficient is related to the Reynolds number[15].

$$C_d = \frac{24}{R_e}, R_e \leq 1 \tag{5a}$$

$$C_d = \frac{24}{R_e}\left(1 + 0.14{R_e}^{0.7}\right), 1 \leq R_e \leq 1000 \tag{5b}$$

and , the Reynolds number R_e is expressed as

$$R_e = \frac{\rho_a D_d u_s}{\mu_a} \tag{6}$$

Here, D_d is water droplet's diameter, u_s is velocity difference between water droplet and air , μ_a is air viscosity.

3. TWO PHASE MODEL OF FALLING DROPLET IN AIR

Considering the influence of freezing temperature on the physical parameters of water droplet and air, the air parameters are modeled with the default values (the temperature range of physical parameters is 200K to 1600K). For water drop, the freezing control mode (T<273.15K) is added into the original model (273.15K to 373.15K).

The model of free falling water-droplet in air is shown in Figure 1. The initial radius and height of round water droplet is R and h, the size of air field is B*H, and gravity g is considered at the same time. Concretely, R=2 mm, h=90 mm, B=20 mm, and H=100 mm. During the free falling process, water-droplet is affected by air resistance and air temperature Tg, and there is a heat transfer between water-drop and air. The characteristics of water-droplet during falling, including deformation, velocity and temperature change are studies.

To describe the comprehensive movement of water droplet, the fluid model used in the numerical calculation is a multi-physical field model, set with two-phase laminar flow, level set and non-isothermal flow. The surface tension of water drop in air is 0.0072 N·m, and the deformation grid domain is used to simulate the deformation of water droplet. The mesh of the numerical model is based on the principle of fluid dynamics refinement, and the boundary layer grids are set at the boundary of water droplet. The grids are shown in Figure 2. There are 2938 elements for the water droplet domain, and the grid quality is close to 1 (1 is the highest grid quality)

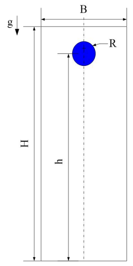


Figure 1: Two phase model of falling water-droplet

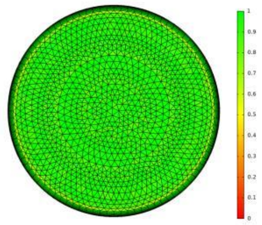


Figure 2: Grids of water-droplet and the quality

4. RESULTS

Figure 3 shows the specific shape of water-droplets (at 283.15K) in different temperatures. In falling process, water droplet changes from initial round type to other shapes. In air at 293.15K, the process of water-droplet deformation is, round-ellipse-ball hat-straw hat shape. In air at 283.15K, the deformation process is similar to that at 293.15K, but the vertical ellipse deformation occurs at 0.02 s. The deformation in freezing environment is obviously different from that in room temperatures. For example, after 0.08 s in air at 263.15K, the water-droplets elongated significantly in vertical direction, resulting in melon seed shape. With further decrease of temperature, the vertical elongation decreases, and the shape is similar to human face.

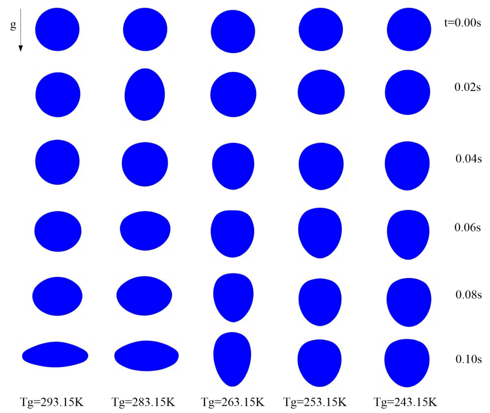


Figure 3: Shape variation of falling water-droplets in different temperatures

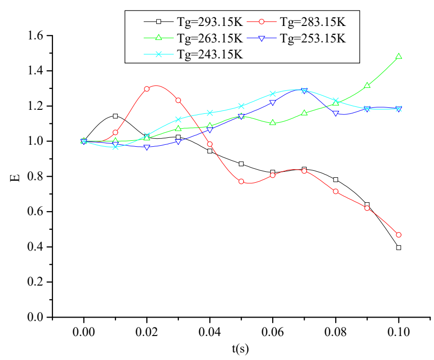


Figure 4: Change of water drop deformation ratio E during falling

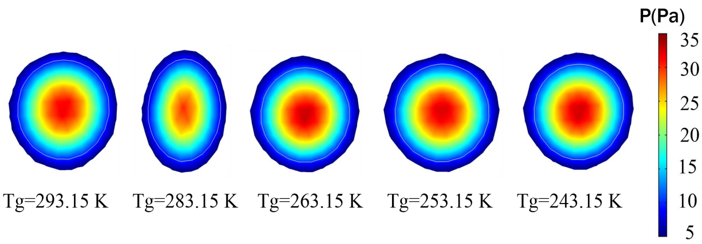
The deformation ratio E is used to describe the deformation degree of the droplet. The deformation ratio E is defined as the ratio between vertical length and horizontal length. For spherical droplets, E=1. For a flat ellipsoid, E<1. For a vertical ellipsoid, E>1. Figure 4 shows the deformation ratio curves. During falling process, before t=0.04s, the shape of water droplets are almost like to each other, except that in air at 263.15K. After t=0.04s, water-droplets in room temperature present oblate ellipsoid shape, while water-droplets in freezing temperature present oblong ellipsoid shape.

It can be seen from Table 1, all the Reynolds numbers are less than 400, and the free falling process of water droplets belongs to two-phase laminar flow. However, the falling velocity and Reynolds number of water droplets in the freezing temperatures are significantly higher than those in the room temperatures, which are increased by about 2 times at 0.10 s. In this paper, Froude number is less than 10, Weber number is less than 1, and Ohnesorge number is less than 0.0011.

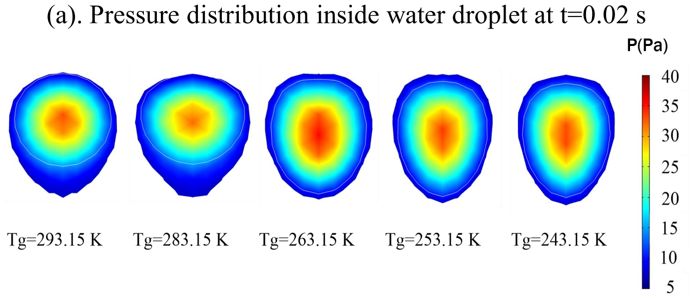
Table 1: Parameters of falling water droplet at t=0.10s.

Tg(K)	Velocity(m/s)	Equivalent diameter(mm)	Reynolds number	Froude number	Weber number(10^{-4})	Ohnesorge number(10^{-4})
293.15	0.71	3.27	153.57	3.94	272.38	10.75
283.15	0.91	3.01	193.99	5.31	432.03	10.71
263.15	1.29	3.16	327.40	7.34	979.83	9.56
253.15	1.34	2.96	342.20	7.88	1033.52	9.39
243.15	1.28	2.96	349.48	7.49	972.00	8.92

When water drops freely, its velocity changes, and its internal pressure also changes due to the interaction of gas-liquid two-phase flow. Figure 5 (a) and (b) are the internal pressure distribution nephogram of the water drop at 0.02 s and 0.06 s respectively, and the white frame is the outer edge of water drop. It can be seen from the figures that the internal pressure of water drop is high in middle position. At 0.02 s, the maximum internal central pressure is 31.73 Pa at 293.15K, 30.09 Pa at 283.15K, 32.72 Pa at 263.15K, 32.36 Pa at 253.15K and 32.52 Pa at 243.15K, respectively. The pressure is the lowest at 283.15 K and the highest at 263.15K, with a difference of 8.74%. At 0.06s, the maximum internal central pressure is 32.91 Pa at 293.15K, 32.03 Pa at 283.15K, 35.45 Pa at 263.15K, 33.78 Pa at 253.15K and 33.31 Pa at 243.15K, respectively. The pressure is the lowest at 283.15 K and the highest at 263.15 K, with a difference of 10.68%.

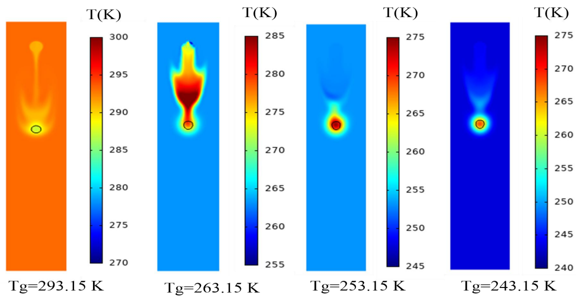


(a). Pressure distribution inside water droplet at t=0.02 s

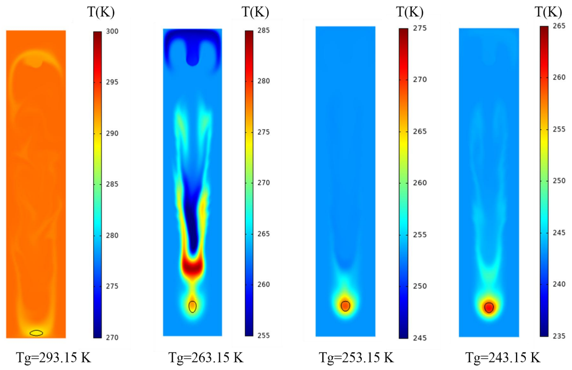


(b). Pressure distribution inside water droplet at t=0.06 s

Figure 5: Pressure distribution cloud inside water-droplet



(a). Temperature distribution at t=0.06 s



(b).Temperature distribution at t=0.10 s

Figure 6: Temperature distribution of the air-water two phase model

As shown in Figure 6, the black frame is the outer edge of water droplet. The change of temperature distribution of water drop is clearly shown at different time. Water droplet is heated gradually in air at 293.15K, firstly with a splash shape at 0.06 s, and then rise to about 289K at 0.10 s. It is cooled by the freezing air. In air at 263.15K, there is a high temperature domain above the water droplet. The temperature of water-droplet drops to about 275K, and there is a cup-shaped high temperature region at the tail of water droplet with about 280K at 0.06 s. The temperature of water droplet drops to about 273K, and there is a necklace shaped high temperature region at the tail of water droplet at 0.10 s. When the air temperature is as low as 253.15K and 243.15K, the droplet temperature decreases rapidly and the change of ambient air temperature is not apparent. The internal temperature of the droplet drops to 270K and 260K respectively. The high temperature region in the tail of water droplets becomes weak and shallow.

5. CONCLUSIONS

In this paper, the hydrodynamics analysis of water droplet falling in room temperature and freezing temperatures is carried out, based on the coupled model of two phase flow and heat transfer in fluid. The main conclusions are as follows:

(1) In falling process, air temperatures affect the deformation of water droplet a lot. At the same time 0.10 s, it is straw hat shape in room temperature, but it is human face shape in freezing temperatures.

(2) Water-droplet velocity experiences a fluctuation process, firstly speeding up — then slowing down — and speeding up again. Compared with room temperature, water droplet in freezing temperatures has the higher falling velocity, larger Reynolds number, larger Froude number, larger Weber number and lower Ohnesorge number.

(3) There are a little pressure change at the inner of water droplet in different temperatures. At 0.06 s, the water droplet inner pressure is the lowest in air at 283.15 K, but the highest inner pressure is in air at 263.15 K, with a difference of 10.68%.

(4) There are great differences in the temperature distributions. When air temperature is 263.15K and droplet temperature is 283.15K, there is a region with higher temperature than that of droplet itself in the tail, and it is a necklace shape.

ACKNOWLEDGEMENTS

This work has received help from the Institute of refrigeration and cryogenic engineering, and the Fundamental Research Funds for the Central Universities.

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